Optimal Materials and Deposition Technique Lead to Cost-Effective Solar Cell with Best-Ever Conversion Efficiency

Based on NREL and Solar Junction technology, the commercial SJ3 concentrator solar cell—with 43.5% conversion efficiency at 418 suns—uses a lattice-matched multijunction architecture that has near-term potential for cells with ~50% efficiency.

2012 R&D 100 50th ANNIVERSARY

The Best Efficiency at a Competitive Cost

Multijunction solar cells have higher conversion efficiencies than any other type of solar cell. But developers of utility-scale and space applications crave even better efficiencies at lower costs to be both cost-effective and able to meet the demand for power. The SJ3 multijunction cell, developed by Solar Junction with assistance from foundational technological advances by the National Renewable Energy Laboratory, has the highest efficiency to date—almost 2% absolute more than the current industry standard multijunction cell—yet at a comparable cost.

So what did it take to create this cell having 43.5% efficiency at 418-sun concentration? A combination of materials with carefully designed properties, a manufacturing technique allowing precise control, and an optimized device design.

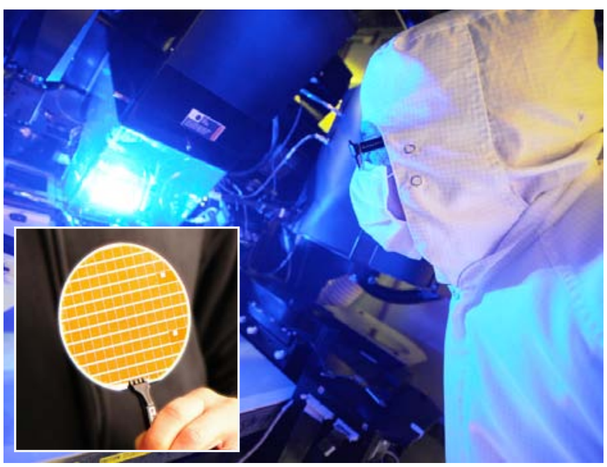

Figure 1. Solar Junction's SJ3 solar cell—with tunable bandgaps, lattice-matched architecture, and ultra-concentration tunnel junctions—is based on NREL's pioneering multijunction work, including a multijunction high-efficiency cell structure and dilute-nitride material. The large photo shows the molecular-beam epitaxy (MBE) deposition system, and the inset is the completed SJ3 wafer. *Photos from Daniel Derkacs, Solar Junction, NREL/PIX 21386 and 21387*

Creating Perfect Materials

A key to the SJ3 success has been this: finding the right material for a bottom junction that has optimal values for the material characteristics of bandgap and lattice constant (see sidebar). Solar Junction and NREL solved this conundrum by using dilute-nitride alloys; a few percent of nitrogen and indium are incorporated into gallium arsenide (GaAs) to tune the bandgap to the desired value of 1 electron-volt (eV) while maintaining the original lattice constant of GaAs (see Figure 4).

The SJ3 architecture is a three-junction design (see Figure 2), with an upper cell of indium gallium phosphide (InGaP), a middle cell of GaAs, and a lower cell of gallium indium nitride arsenide, with some antimony (GaInNAs[Sb]). This lower cell is the special dilute-nitride material at the heart of this innovative solar design.

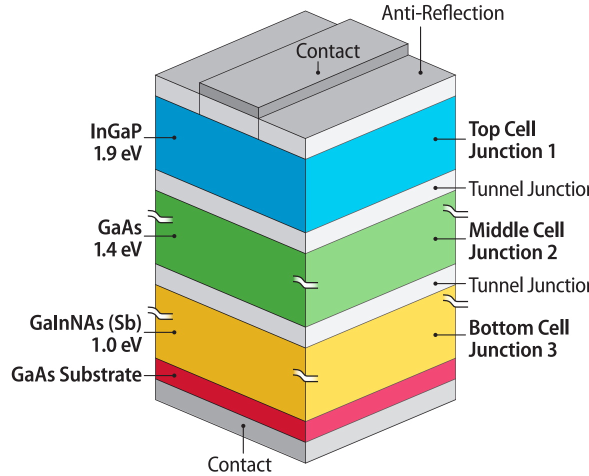

Figure 2. A schematic of the SJ3 multijunction cell highlights the three junctions and their chemical compositions and bandgaps (in electron-volts). The top cell uses the high-energy end of the solar spectrum, and lower cells use correspondingly lower-energy portions of the spectrum.

Growing Perfect Junctions

Unfortunately, growing high-quality dilute-nitride material has not been possible using the industry-standard deposition technique of metal-organic vapor-phase epitaxy (MOVPE). But Solar Junction has overcome this obstacle by employing a well-established manufacturing technique used by the cell phone and solid-state lighting industries—namely, molecular-beam epitaxy (MBE).

Solar Junction did not invent MBE, but the company did figure out how to use it to produce new materials with the necessary high quality and tightly controlled characteristics. This deposition technique excels at precisely controlling epitaxial growth, thus allowing very thin layers to be deposited with sharp interfaces and minimal contamination of the material.

Compared to MOVPE, MBE can grow superior tunnel junctions, which are very thin layers that electrically connect the various layers within the multijunction structure. To exhibit high performance for ultra-concentration—in the 500- to 1000-sun range—the tunnel junction layers must be very thin, highly doped, and have very abrupt interfaces. These requirements are well suited to the physical processes of MBE.

Overall, MBE can grow excellent tunnel junctions and dilute-nitride materials, and has substantially more uniform deposition than MOVPE, which drives yield and cost, and ultimately improves the performance of the final solar device .

Pushing Toward 50%

Currently, the SJ3 solar cell has three junctions. But it is possible in theory and practice to add more junctions to push the efficiency toward 50%.

We will need to further engineer other materials with the appropriate bandgaps to capture more of the solar spectrum, and materials with lattice matching to prevent degraded cell performance and increased cell cost. The next logical step will be to add a lowermost, fourth junction.

Bandgaps, Lattice Constants, and All That Jazz

The bandgap of a material is the energy required to excite an electron from the valence band to the conduction band of that material so that the electron can contribute to the electrical current of the solar cell. The solar spectrum consists of light across a wide range of energies. Light is absorbed by a material if the light's energy is greater than the material's bandgap. Energy above the bandgap is lost as heat, and below the bandgap the energy is not absorbed and cannot be used to generate electricity. The multijunction solar concept is to combine several layers with differing bandgaps—with the top layer absorbing the high-energy light, and lower layers absorbing the lower-energy light.

Bandgap is important, but a material's lattice constant is also critical. Solar Junction grows layers epitaxially, which means that the structure of the first atomic layer deposited is mimicked in the second atomic layer, and so on, through the thickness of the entire junction. The result is a lattice-matched crystal, in which the spacing of atoms in one junction is the same as that in the other adjacent junctions (see Figure 3). This constant spacing is required to produce layers without crystal defects, which degrade cell performance.

In pioneering work by NREL, dilute nitrides have been developed to have both the proper bandgap and lattice constant for optimal performance in multijunction solar cells (see Figure 4).

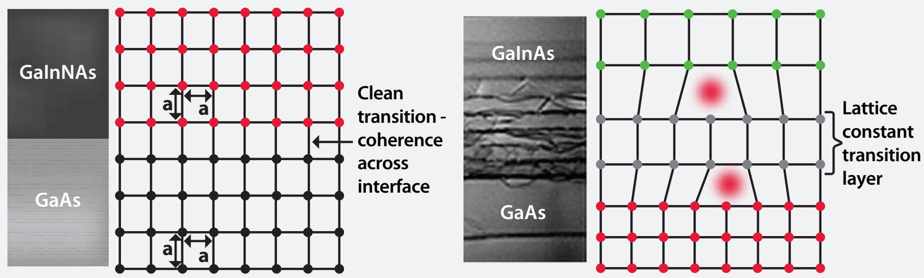

Figure 3. (Left) Transmission electron microscope (TEM) image shows lattice-matched materials, with an illustration to the right of both layers having the same lattice constant and showing no strain or distortion of the crystal structure. (Right) TEM image shows lattice-mismatched materials, with an illustration to the right showing the strain of the crystal structure transitioning from a lower to an upper layer with smaller and larger crystal lattice constants, respectively. A network of defects is visible as the irregular spaghetti-like dark lines. Any such defects that extend into the active region of the device lower its performance.

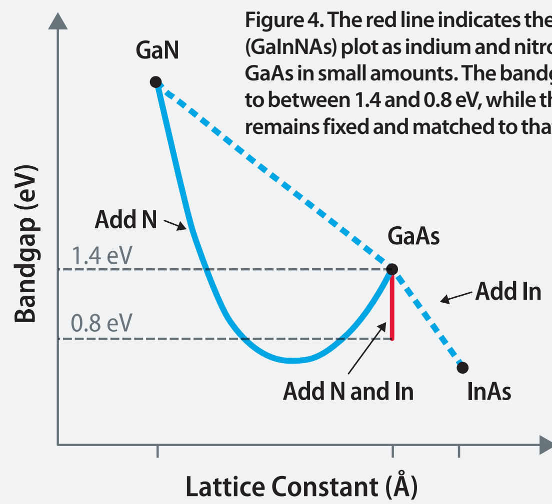

Figure 4. The red line indicates the dilute-nitride alloy (GaInNAs) plot as indium and nitrogen are added to GaAs in small amounts. The bandgap can thus be tuned to between 1.4 and 0.8 eV, while the lattice constant remains fixed and matched to that of GaAs and Ge.

For More Information

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NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

NREL/FS-2000-55741 • July 2012

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